Technology Assessment for Defense Against Asteroids or Comets

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This paper presents an overview of promising defense strategies against asteroids or comets that may be discovered and found to be on a collision course with Earth. It reviews the technology needed to make defense missions against this kind of threat feasible, assessing threat conditions that can be met by currently available space technology and launch capability and those that require major technology advances. Issues of concern include launch, orbit transfer, terminal guidance, automation and robotics, as well as possible options for deflecting the threatening object from its collision course, or destroying it. Currently used space mission analysis and design procedures can be applied here to select the most dependable and cost-effective mission and system concept and identify technology advances that are required for its implementation.

Introduction

The potential threat of catastrophic impacts on Earth of asteroids or comets has become more widely recognized, and several major conferences on this subject, preceding the current Workshop, have been held in the past years. The recently published comprehensive book entitled "Hazards due to Comets and Asteroids", edited by Gehrels (1994) contains information that was presented at the 1993 University of Arizona Conference by the same title, an up-to-date source of knowledge and ideas concerned with the nature of the threat and the means to defend against it. As such, it also is the source of some of the material presented in this paper.

This article gives an assessment of technologies that will be essential in future missions designed to defend against the threat. Along with various mission concepts advanced in the literature - and in this Workshop - and techniques for their implementation, it lists specific technology fields critical to undertaking defensive action, in particular those that need further advances and evolution.

Technologies that may evolve in future decades to become available for conducting defense missions against threatening near-Earth objects (NEOs) are difficult and risky to project. Evolution generally tends to outpace projections. This is well illustrated by the 35 years of past space technology growth. Similarly, any large resources that would be available for achieving this evolution and for undertaking a defensive mission, are highly unpredictable. Bold projections are needed, nevertheless, to help stimulate technical evolution, and the process may benefit from the growing recognition of the threat, in general, and from global cooperation to support technical preparedness (Morrison and Teller, 1994). Technology assessments and projections presented in this article should be viewed in the light of these comments.

The following sections address issues of technical preparedness for NEO defense; principal defensive mission concepts and mitigation techniques; NEO deflection or destruction options, technologies available for this purpose; and technology drivers, limiting factors and constraints. Methods of mission and system engineering used for current more conventional missions, and their application to NEO defense missions also will be discussed.

Principal Threat Mitigation Techniques

Threat mitigation techniques that are currently of principal interest include NEO deflection by propulsive means, by direct impact, also known as kinetic energy deflection, and by nuclear detonation. Other techniques being proposed include NEO surface heating and evaporation by ground- or space-based lasers or space-based solar reflectors. An impulse generation technique that would use mass drivers such as electromagnetic linear accelerators for ejection of processed NEO surface material (Canavan, 1994) also has been proposed, but it involves highly complex surface operations and requires a power source in the Megawatt range. Only the three first-mentioned threat mitigation techniques will be considered here. Specific quantitative impulse requirements and interceptor initial mass at Earth departure typical for these defense modes are given in the next sections to indicate their respective usefulness, effectiveness and cost.

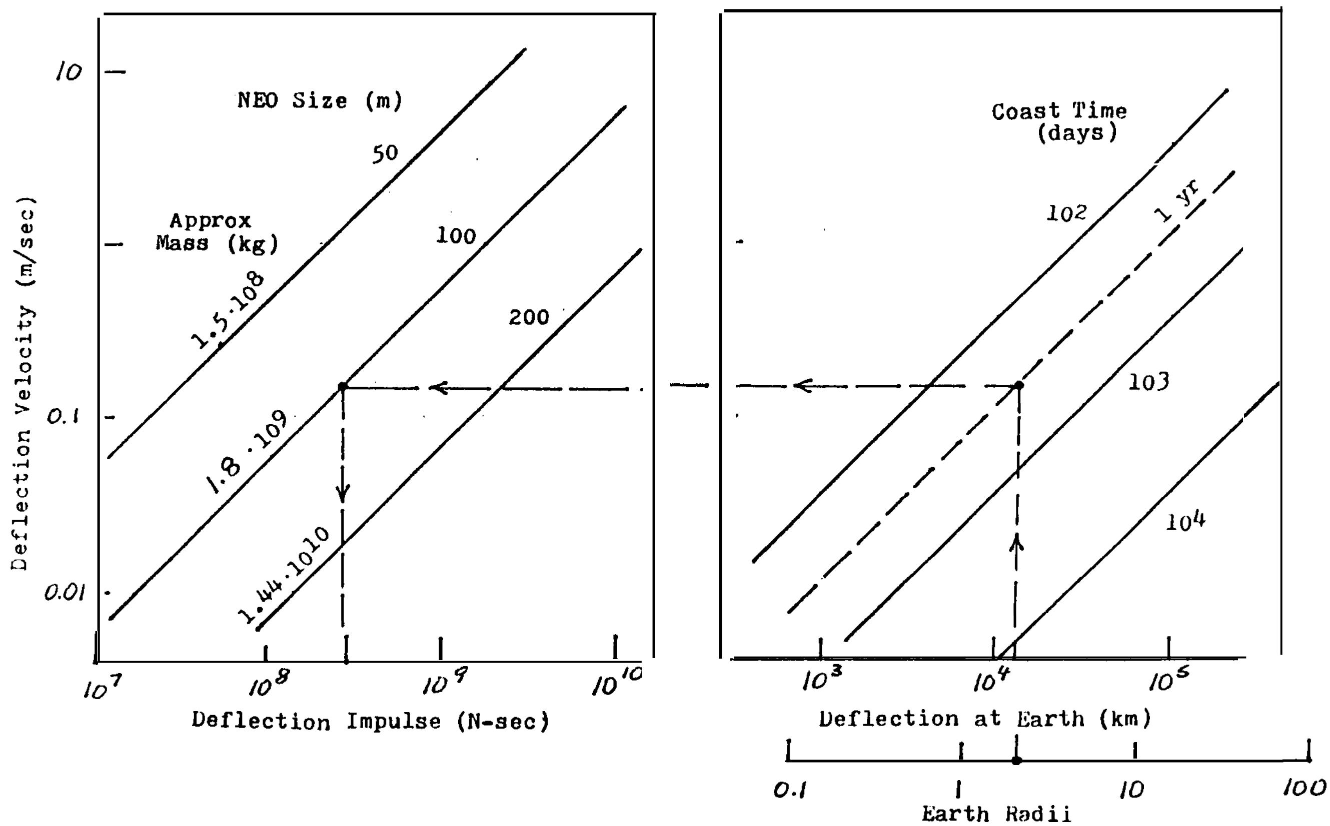

Figure 2 -Relation Between Asteroid Size, Deflection at Earth, Coast Time, Deflection Velocity and Deflection Impulse

Interceptor Mass Data for the Principal Deflection Modes

From the impulse requirements derived above the corresponding initial mass of the interceptor spacecraft can now be determined for the three principal deflection modes considered here. It depends on the final mass transferred to the target and the amount of propellant needed in the process.

In the propulsive NEO deflection mode the interceptor system must generate three separate velocity impulses: first, to start the transfer from Earth; second, to apply retro-propulsion at the target, for soft landing; and third, to deliver the required target deflection impulse on the surface. The third impulse is by far the largest.

The kinetic energy deflection mode, by contrast, requires only a single velocity impulse, that of starting the outbound transfer. The nuclear detonation mode requires one or possibly two velocity impulses, the second one only if zero-velocity rendezvous for a standoff blast is to be achieved. Therefore these two modes require much less propellant than the propulsive mode, and consequently the required initial mass is very much smaller (see below).

For the propulsive mode, the initial interceptor mass is given approximately by

$$M_i = M_{p,3} * \exp[(\Delta V_1 + \Delta V_2)/gI_{sp}] \qquad (1)$$

where $M_{\eta,3} = M_a * \Delta V/(g\, I_{sp})$, and ΔV_1 and ΔV_2 are the required first and second velocity impulses applied at departure and arrival. The relatively minor effect of tankage, structure and other interceptor subsystem mass is neglected in this approximation. Figure 3 shows the interceptor initial mass M_i versus the time remaining after the intercept to reach Earth's vicinity, for NEOs of 50, 100 and 200 m size. Near-term propulsion technology with 500-sec specific impulse (solid lines) and future technology with 1000-sec specific impulse (dashed lines) are reflected

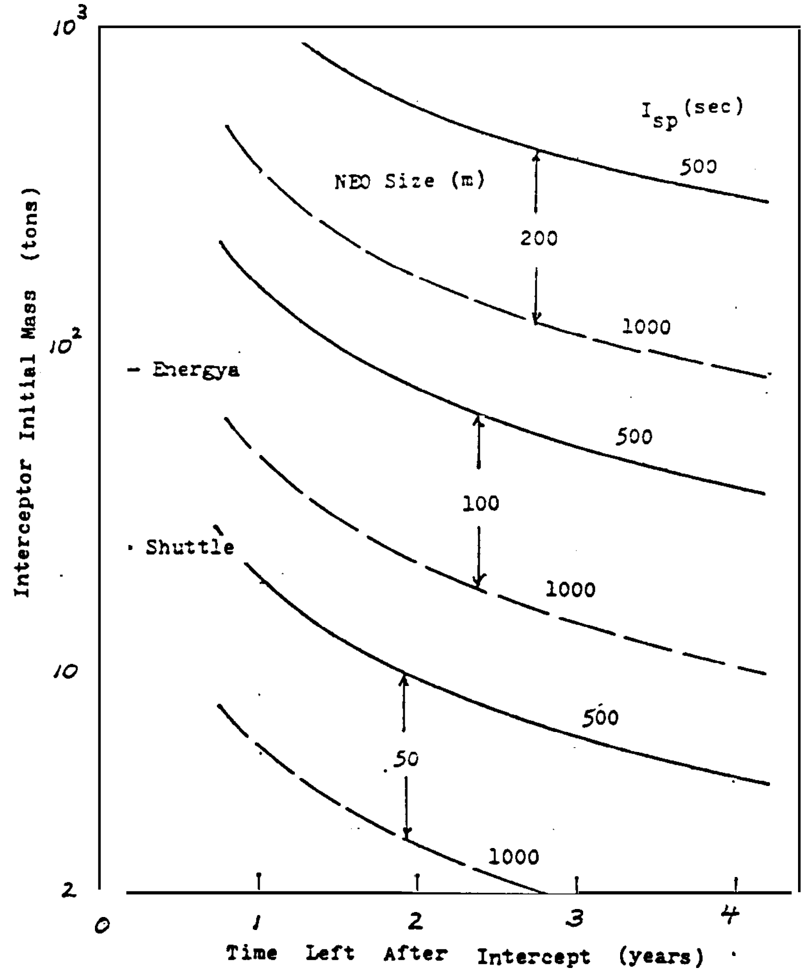

Figure 3 - Interceptor Initial Mass vs Coast Time Remaining after Deflection for Three NEO Sizes (Propulsive Deflection Mode)

in the figure. The second set of M_i values is 3.5 to 4 times smaller owing to the dominant exponential effect of the I_{sp} increase in equation (1). The results shown are based on an assumed near-minimum energy interceptor transfer trajectory with 3 km/sec hyperbolic excess velocity at Earth departure, and 2 km/sec arrival velocity at the target, prior to the retro-maneuver. Only the initial mass for the 50-m NEO intercept is seen to be well within the Space Shuttle's maximum payload capacity of about 25 tons, without the benefit of advanced propulsion technology, and for elapsed times as low as 1 year. For the 100-m intercept mission the interceptor initial mass would be within the Shuttle's payload capacity only for the higher-I_{sp} propulsion technology, and for elapsed times of at least about 2 years. With the much higher, 80 to 90 ton payload capacity of the powerful Russian Energya launch vehicle a 100-m NEO defense mission could be performed using near-term propulsion technology, given at least 2 years of elapsed time.

The required burn time of the rocket landed on the NEO surface will be a major concern considering the very large amount of propellant involved. Figure 4 shows the burn time, t_b (dashed lines), for the propellant mass needed in the 50 and 100-m NEO deflection missions, assuming a thrust force of $4 * 10^4$ Newton. The propellant mass $M_{r,p}$, is shown in the same graph by solid lines. Burn times range from 25 to 101 minutes for the 100-m, and from 3 to 13 minutes for the 50-m NEO deflection impulse. Clearly, the excessive burn time required in some of these cases would be unacceptable and indicate that a higher thrust level than that assumed here is needed. Note that the burn time shown is independent of the specific impulse since it is defined by $t_b = M_a * \Delta V/F$, where F is the thrust force.

For comparison, initial mass data for the kinetic energy and the nuclear detonation (surface blast) threat mitigation modes, adapted from Solem and Snell (1994), are shown in Figure 5. In this figure, the M_i values vary with the NEO distance, R_I, at the time of interceptor launch and the NEO size, d (in meters),. They apply to greatly different target encounter conditions and extremely short response times, of only few weeks. The NEO approach velocity is assumed as 25 km/sec, and relative intercept velocities range from 40 to 50 km/sec, i.e., the engagement reflects a head-on encounter after a critically late threat detection. The results were derived originally for a 1000-km deflection distance at Earth, to shift the impact from a land mass to the nearest ocean. Reinterpreted for a deflection distance of 2 Earth radii, this requires increasing the initial interceptor mass values by a multiplication factor of 15

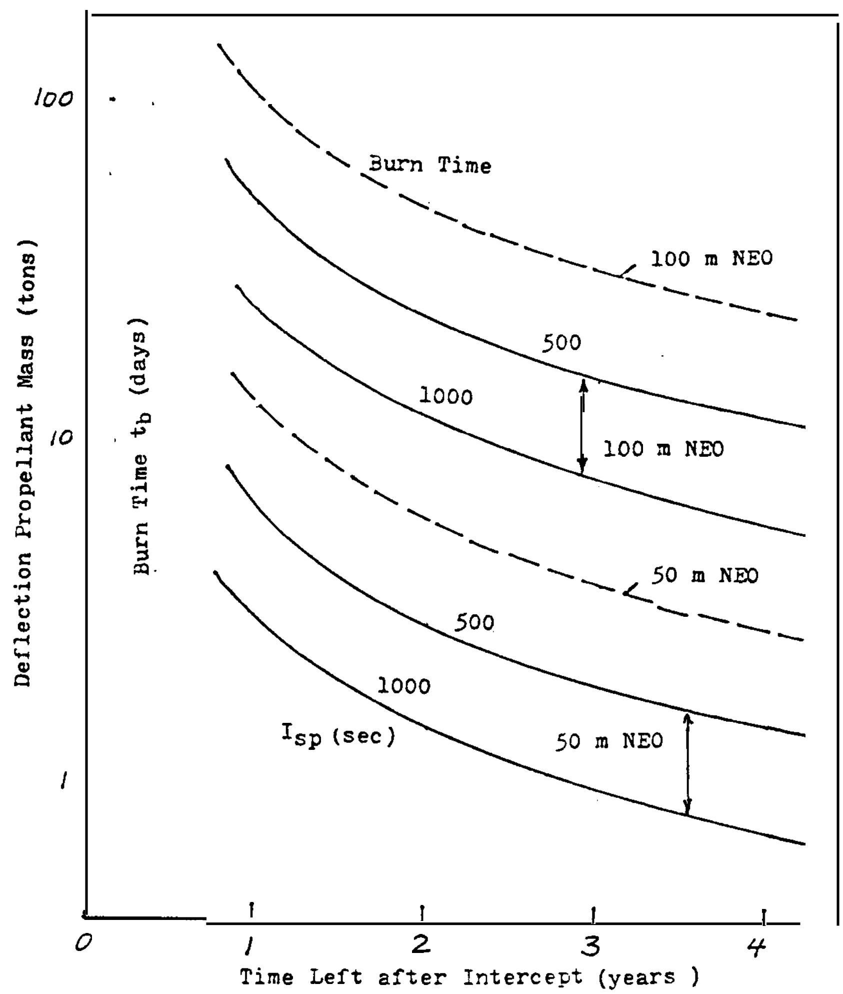

Figure 4 - NEO-Deflection Propellant Mass and Burn Time for a 50 and 100m Diameter NEO vs Remaining Coast Time

(see the numbers shown in parentheses in the figure). For this 12 times larger deflection distance the kinetic energy mitigation mode (left hand graph) of a 100-m object at an initial range of 0.01 AU requires an initial interceptor mass of 15 kilotons, while for a 0.1 AU initial range it would require only 1.5 kilotons.

Results obtained for the nuclear detonation mode (right-hand graph in Figure 5) are presented in terms of the same parameters. They show a mass reduction of about three orders of magnitude, e.g., for d = 100 m and R_I = 0.01 AU, M_i is only 15 tons compared with the corresponding 15 kilotons obtained for kinetic energy deflection, again assuming a shift of 2 Earth radii.

Referring back to the results obtained for propulsive deflection, (Figure 3), it is apparent that the two high-energy modes require a many orders-of magnitude smaller interceptor mass. Results such as those given here and in several other references (see Gehrels, 1994) lead to the conclusion that an effective defense against NEOs larger than 100m and allowing only little reaction time demands the use of the nuclear deflection mode, except under conditions where the simpler kinetic energy mode is adequate.

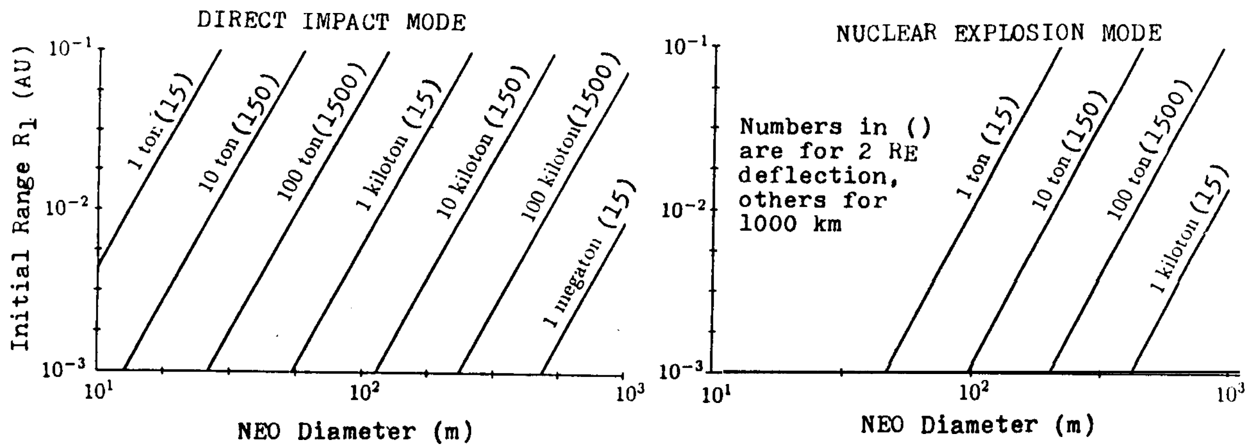

Figure 5 - Interceptor Initial Masses for NEO Deflection by Kinetic Energy and Nuclear Explosion Modes, Depending on NEO Size and Initial NEO Distance (Ref. Solem and Snell, 1994)

Technology Assessment

Key Technologies Essential to NEO Defense

Data presented above indicate that defense mission requirements for the least demanding NEO threat conditions can be met by today's technology, e.g. for NEOs of less than 100 m diameter and sufficiently long warning times, of the order of several years. The launch capability of the Space Shuttle or some of the largest expendable launch vehicles available today can support defense missions requiring from 15 to 85 tons initial mass in Earth orbit, as shown in Figures 3 and 5.

Advances in spacecraft and space mission technology anticipated in the near future will allow responding to a much wider spectrum of NEO threats. Of particular interest are advances in propulsion technology, spacecraft and subsystem miniaturization, refinement of terminal navigation and guidance, and greater automation and robotics capability.

Propulsion Technology

Extensive efforts to increase the specific impulse of space propulsion systems have been in progress in laboratories and test facilities over several decades, both in chemical and electric propulsion. After reaching a mature state, this advanced technology will be applicable to NEO threat defense missions, and will greatly enhance performance.

Technology advances of particular interest here are those in nuclear-thermal rocket engines with specific impulse increasing up to 1000 sec (Jones, 1992a; Venetoklis et al., 1994; and Willoughby et al., 1994). Also of interest are electric propulsion systems such as ion and plasma thrusters with specific impulse in the 3000 to 5000 sec range (Jones, 1992b; and Pollard et al., 1993). Compared with current high-performance cryogenic chemical rockets, such systems achieve very large reductions in propellant mass ratios for high- ΔV missions, as indicated by the equation

$$M_p/M_f = \exp(\Delta V/g\, I_{sp}) - 1 \qquad (2)$$

where M_p and M_f are the propellant mass and final mass respectively. Assuming as an example a 5000-kg final mass and a total ΔV of 3 km/sec, an I_{sp} increase from 450 sec (cryogenic chemical rocket) to 3000 sec (ion or pulsed plasma thruster) reduces the propellant ratio from 0.973 to 0.107, and hence, the propellant mass from 4,865 to 535 kg. Considering the much greater ΔV requirements of some cases previously discussed, a propellant mass reduction of 15/1 or 20/1 would be achievable by this increase of the specific impulse.

The required propulsion system power, proportional to the product of thrust force and I_sp is a factor in assessing benefits and drawbacks of applying this new technology. In the above example pulsed plasma thrusters would require 113 kW of propulsion power to produce the very low thrust force of 5 N, which implies a thrust phase duration of 37 days. Generally, this long thrust phase can be accommodated in the mission design. The necessary power can be provided by a space-nuclear-power generator such as the SP 100 system which has been under development for a number of years. The alternative of a solar-electric power source appears impractical, unless the power level and hence, the thrust force can be significantly reduced, provided a further increase in thrust time is acceptable. This kind of trade is typical for introducing advanced technology to enhance system and mission capabilities.

The greatly reduced propellant mass inherent in applying electric propulsion technology reflects in major spacecraft initial mass reduction and thus a smaller-size, less expensive launch vehicle. The technique of planetary gravity assist that has been proposed to reduce NEO-intercept ΔV requirements (Landecker and Gurley, 1992) would become unnecessary, and the longer trip time and greater mission profile complexity associated with it are avoided. Also, the need for on-orbit assembly of an excessively large and massive interceptor may be circumvented, along with the complexity and cost of such operations, multiple Shuttle launches, and the loss of time inherent in the process.

Miniaturization of Space Systems and Spacecraft Components

The mass of spacecraft and subsystems have been greatly reduced in the last two decades, notably in structures, power generation and control, and electronic subsystems. In Earth-orbiting spacecraft these advances have led to major mass and size reductions, with gross mass as low as one half to one quarter of the mass of earlier-generation vehicles, 10 to 20 years ago.

In NEO defense the benefits of this evolution can lead to initial and final mass reductions . However, in missions with a large nuclear payload or with a large propellant mass, the shrinkage of carrier mass alone becomes less significant in the overall mass budget. As shown by Gurley et al. (1994) in a comparison of mass characteristics of a system with chemical vs. one with advanced (nuclear-electric) propulsion, only the former benefited enough from miniaturization and subsystem mass reduction to permit the use of a smaller, lower-cost launch vehicle. Thus, any weight benefits from miniaturization will have to be assessed relative to advances in other areas of space system technology.

Terminal Guidance

The high precision required for delivering the NEO interceptor at exactly the intended location on or above the surface of the small target object demands an extremely high terminal guidance accuracy.

In past and current planetary flyby and orbit missions, terminal guidance accuracies of several and even tens of kilometers have been considered adequate and have been achieved consistently by correction maneuvers performed days or weeks before arrival at the target. Closest approach distances in such missions typically range from tens to hundreds of km. Terminal guidance corrections are performed with the aid of Earth-based or spacecraft-based error detection techniques. Currently, autonomous navigation techniques without dependence on Earth-based tracking and command are being studied intensively, as they tend to simplify mission operations and reduce cost.

In an asteroid or comet intercept, terminal guidance must be refined to reduce the approach error by several orders of magnitude, to a range of hundreds, or even tens of meters, depending on target size and intended approach geometry.

Table I lists some intercept mission modes and summarizes terminal guidance requirements and issues of concern. Modes (a) and (b) achieve target deflection by kinetic energy, chemical high-explosive, or nuclear energy transfer. Mode (c) may be used to initiate surface operations such as implanting a propulsive or explosive energy transfer device, or to explore physical target characteristics, e.g., in a precursor mission conducted prior to threat mitigation. Modes (d) and (e) may serve various options such as close observation or deferred - time detonation above the surface.

TABLE I

Target Acquisition and Terminal Guidance Requirements

Intercept Mode	Mission Type	Approach Velocity ($km\ s^{-1}$)	Required Acquisition Range[a] (km)	Required Terminal Accuracy[a] (m)	Issues and Concerns
(a) Direct impact at high velocity	Close intercept: Kinetic energy deflection; Nuclear explosive deflection or fragmentation	15–30	3000	50	Early acquisition, prompt lateral guidance maneuver; Critical guidance accuracy with advanced sensor technology
(b) Tangential impact at high velocity	Close intercept: Kinetic Energy Deflection; Nuclear explosive deflection or fragmentation	15–30	3000	20	Early acquisition, prompt lateral guidance maneuver; Critical guidance accuracy with advanced sensor technology
(c) Soft landing, following retro maneuver	Distant intercept: Implant energy transfer device or mass driver; Implant nuclear device	2–5	300	100	Early retro maneuver, several days before acquisition[b]; High terminal accuracy; Soft landing adaptable to uncertainty in gravity
(d) Injection into near-circular orbit, following retro maneuver	Distant intercept: Close observation; Deferred detonation, standoff or surface	2–5	300	200	Early retro maneuver, several days before acquisition[b]; Moderate terminal accuracy; Orbit insertion adaptable to uncertainty in gravity
(e) Zero-velocity rendezvous/formation flying	Distant intercept: Close observation; Deferred detonation, standoff or surface	2–5	300	500	Early retro maneuver, several days before acquisition[b]; Moderate terminal accuracy; Requires periodic altitude correction

[a] Rough estimates; 100 to 300 m class target object assumed. Less terminal accuracy required with larger target.

[b] Earthbased relative trajectory information and maneuver commands can be used.

All of these scenarios demand the development of advanced guidance techniques to meet the unprecedented requirements of extremely high terminal accuracy. These accuracy requirements critically depend on the selected encounter mode. A direct frontal impact, mode (a) or a nearly tangential impact, mode (b) are likely to be used in a late-intercept situation (Ahrens and Harris, 1994). Frontal impact requires a lower terminal guidance accuracy than tangential impact and depends less critically on early guidance error detection by the homing sensor, and therefore, appears preferable.

In the distant intercept scenario the optimum orientation of the deflection impulse generally is parallel, or anti-parallel to the heliocentric target velocity, as discussed previously. In this scenario modes (c), (d), or (e) are likely candidates for executing the target deflection at lower guidance accuracy requirements compared with modes (a) or (b). On approaching the zero-range-rate and zero-range-error condition by intermittent retro-thrust application the sensitivity to thrust and coast duration increases, along with rapid improvement of the error detection capability.

In developing sufficiently accurate, dependable terminal guidance capabilities, major demands are placed on sensor technology advances, to provide a large detection range for faint target objects and extremely high angular resolution. Earth-based remote guidance currently uses on-board sensors to provide the required high error-detection accuracy during the final approach to a planetary target. However, the large communication delays of 10 minutes and more, inherent in this technique, are not consistent with instant terminal guidance error corrections necessary when arriving at a small NEO, at the approach speeds involved. Therefore, autonomous guidance will be essential.

Hypervelocity target intercept techniques have been under development by the U.S. Military for ballistic missile defense (Nozette et al., 1994). Such techniques, when available without security restrictions, promise to provide critically needed advances toward solving the difficult autonomous terminal guidance problem, especially under short-response-time conditions.

Automation and Robotics

Advances in automation and robotics will be essential to several phases of NEO defense missions. These include assembly in Earth orbit of separately launched interceptor segments; autonomy of operations near the target or on the target surface such as implanting and operating high-energy propulsion systems or mass drivers, performing subsurface placement of a nuclear explosive, or collecting and processing surface material for propulsive purposes.

At present, spacecraft automation techniques, originally developed for lunar and planetary exploration, are being further advanced for use in a new generation of space exploration missions. The projected international space station requires development of advanced robotic manipulation, assembly and maintenance techniques, to save cost, minimize human operator workload and reduce hazardous task exposure. This evolution is an important step toward automated performance of some of the NEO defense mission phases. Demonstration during the construction of the space station will stimulate further growth of this technology.

Technology Drivers and Limiting Factors

Table II summarizes principal factors that influence the evolution of advanced and novel technology needed for use in NEO defense missions. The issues involved are listed as they relate to various mission phases or activities, grouped into eight categories. Also listed are limiting factors and constraints that apply in each of these advanced technology fields. The last column ranks these developments according to their relative priority: very high, high and medium. High, or extremely high cost, although not listed here, will be a critical constraint on almost all items included in the table.

Mission activities included in the list, but not previously discussed, are tests or demonstrations of feasibility and performance; nuclear device adaptation for NEO defense purposes; and communication and tracking operations.

- Test and demonstration requires novel techniques specifically related to the unprecedented NEO intercept and mitigation tasks. The key technologies discussed above should be included in these demonstrations. Ultimately, a demonstration mission to a non-threatening "NEO-of-opportunity" may have to be flown to attain sufficient realism in testing key operation sequences.

- Nuclear detonation development should include testing of explosives of the type that would be employed for NEO deflection, fragmentation or pulverization, although not necessarily devices of the required actual size and yield. Clearly such tests cannot be carried out on or near Earth but should be performed in deep space. This would require internationalnegotiations and agreement, based on the general, global interest in NEO defense.

TABLE II

Technology Drivers and Limiting Factors

Category of Mission Phase	Technology Drivers	Limiting Factors or Constraints	Priority
1. Test and demonstration	Test facility development and testing	Realism and validity	High
	Precursor missions to NEO	Enough time available	High
2. Launch (*see also* Propulsion)	Launch vehicle capability	Unprecedented vehicle size	Very high
	Launch readiness	Long standby periods	High
	Unprecedented scope	Coordination	Medium
	On-orbit assembly	Feasibility and risk	High
3. Interplanetary transfer (*see also* Propulsion)	Complex mission planning & execution, possibly with gravity assist	Launch windows	Medium
4. Guidance, navigation & control	Target detection, terminal guidance sensing	limitations	Very high
	Pinpoint terminal accuracy		
	Autonomous rendezvous & landing	Risk, safety	High
5. Propulsion (Phases 2, 3 & 4)	High specific impulse	Safety	High
	Endurance & reliability	Development cost & schedule	Medium
6. Nuclear detonation	Control, safety, & high yield	Adequate test program	Very high
		Long development time	
7. Communications & tracking	Comm time delay compensation	Autonomy requirements	High
	Continuous coverage	Possible Sun interference	(NA)
8 Automation & robotics	O as m	Human assistance essential	Very high
	R m m control near or at target	Backups burden design, increase launch weight	High
	Safety & reliability		

• Communication and tracking activities to be employed in the NEO defense context present novel technology requirements. These include the ability to conduct continuous uplink/downlink data transfer during critical mission phases; compensation of communication delay; rapid interpretation of observation data received and immediate reaction in terms of ground-based interceptor control. Rapid detection of, and response to the effect of mitigation activity at the target also is a requirement, particularly if a second (back-up) interceptor is en-route and must be controlled in accordance with observed results achieved by the first interceptor.

Technology Evolution for Conventional Missions and for NEO Defense

One of the principal obstacles to technology advances dedicated to NEO defense requirements is the lack of major funding that would be available prior to the discovery of an actual NEO threat. At best, some technology evolution that is related to general, i.e., conventional space mission objectives can also be utilized for development of future NEO defense capabilities, as a "spin-off".

Figure 6 depicts the relationship between the two inherently related fields of space technology. The scale on the right indicates technology requirements and development criteria of NEO defense missions, increasing from the easiest to the hardest mission demands. The left side indicates technology advances to be expected in coming decades, driven essentially by conventional mission needs, and supported by research and development funding.

The figure indicates that the least-demanding NEO defense missions are feasible based on the present state of technology. Inputs from the NEO defense engineering side may help in directing needed technology developments, without being supported officially.

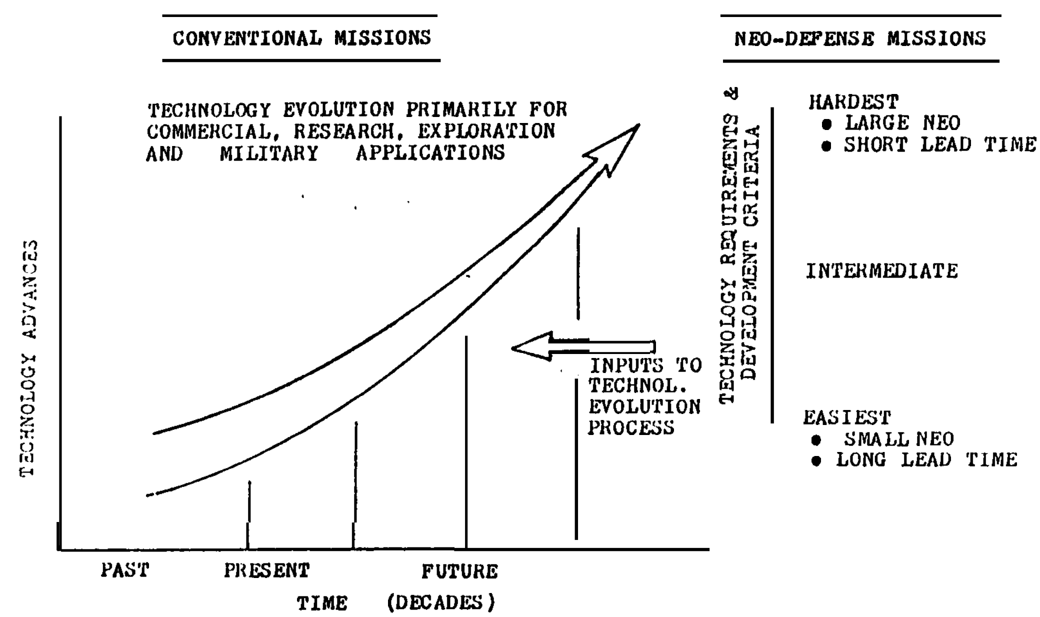

Figure 6 - Technology Evolution Serving Both Conventional and NEO-Defense Mission Needs

Mission/System Design and Technology Requirements Flow

Methodology used in mission and system engineering for finding the most efficient and cost-effective design and operating concepts in conventional space projects can also be applied in the NEO defense field. Figure 7 schematically illustrates the process of selecting the most advantageous mission and system concept among various alternatives. This involves a trade between system design options and technology requirements. The choice may be between a more costly design that can be implemented with existing technology and a less costly design that requires higher technology development expenditures. The selection process is based on a set of applicable figures of merit, listed on the right, that are agreed upon at the start. Extensive iteration of design concepts and technology demands is vital to this selection and decision making process.

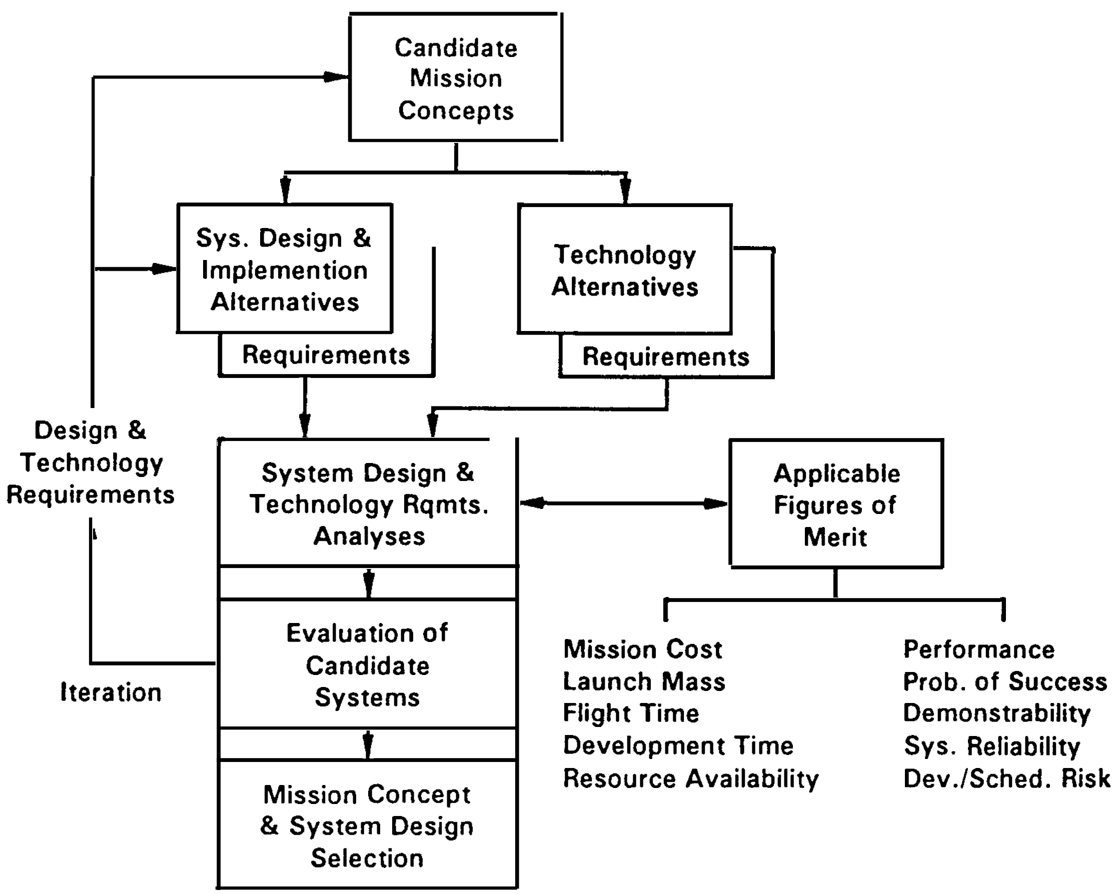

Figure 7 - Methodology of Mission and System Concept Selection

A related technology requirements flow chart is shown in Figure 8. It complements the preceding chart by indicating three levels of technology status - currently available, extended, and entirely novel - that should be assessed in the process of selecting the best mission and system concept. Some assessment criteria listed in the lower part of the chart are used in the feedback and iteration process that leads to the concept selection, including the design, its implementation and operation procedure. The flow charts represent a system engineering approach, discussed in greater detail by Larsen and Wertz (1994), that relates to the requirements trades referred to in this section.

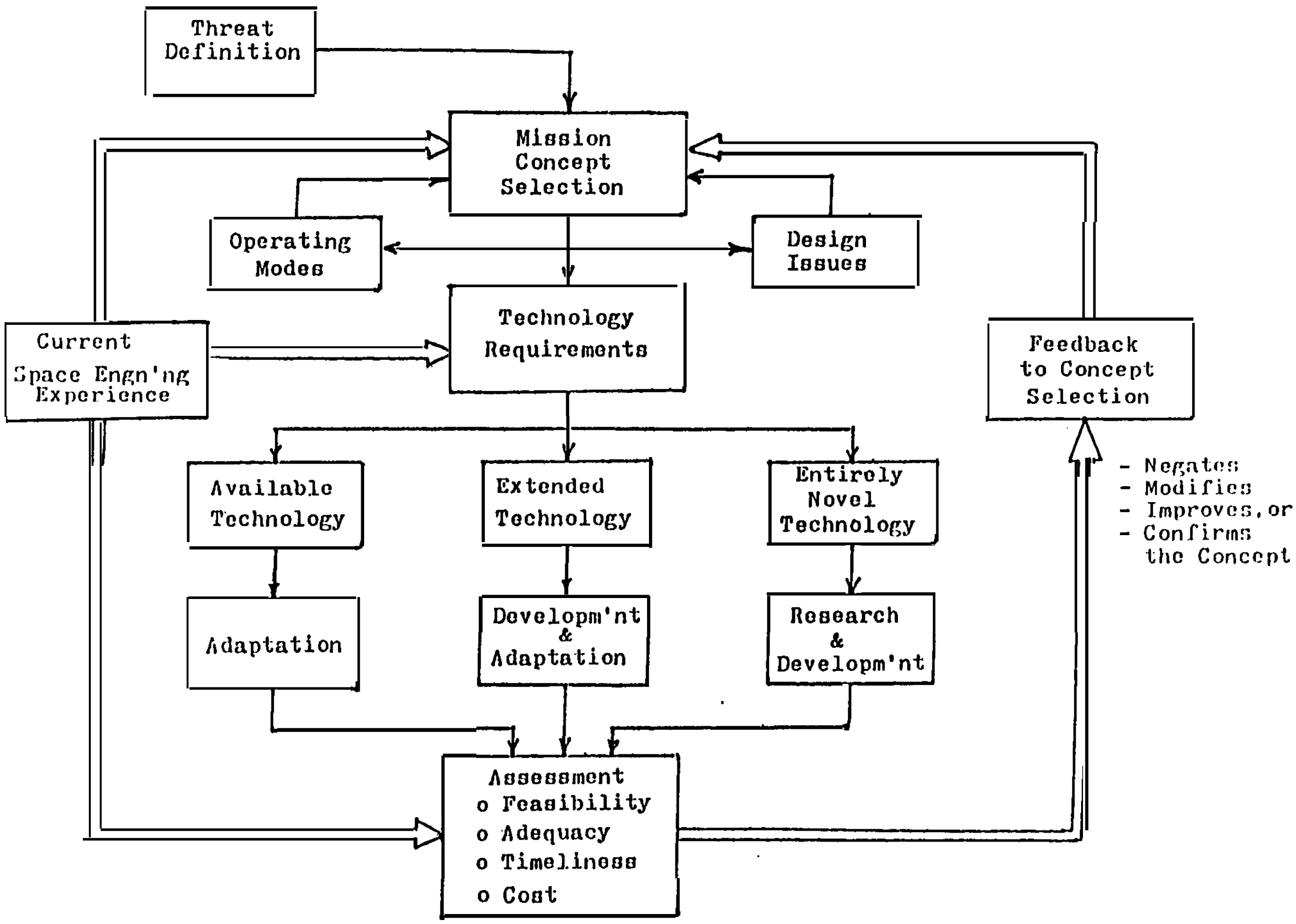

Figure 8 - Technology Requirements Analysis Flow

Preparedness for NEO Defense

There are many constraints and obstacles to being prepared for undertaking a NEO defense mission, now or in the immediate future - except perhaps the least demanding type referred to in the preceding sections. This is due not only to a lack of resources available before a major threat is detected and identified, but also to public indifference in the absence of an identified threat.

To develop and build a system for NEO defense ahead of time, ready to be launched on short notice, would be impractical and probably wasteful. Different types of impact threat will require different types of defense systems, mission modes and scenarios. Also, evolving advanced technologies tend to make a system, built in advance of actual threat detection, obsolete by the time it would be needed. That time might be many decades, perhaps even centuries, from today. New technologies such as those referred to above will make different and potentially more effective defense strategies feasible.

A fundamental dilemma concerning the desired threat response preparedness needs to be resolved: (a) there is no point in detecting a threatening NEO if no feasible program for defense against it is available; (b) a program for defense against a threatening NEO is useless, unless we search for and detect it sufficiently long in advance of the projected impact time (Dixon, 1993).

To resolve this dilemma requires reasonable and economically affordable steps toward developing and maintaining some threat response capability within the framework of current and continually evolving technologies. These steps include:

- Stepped-up search for, and cataloguing of potential NEO threats. Such efforts are now in progress under Space-Watch auspices

- Ongoing mission and system design activities, within existing and advancing technology capability. Results reported in these proceedings are encouraging evidence of the initiation of such activities.

- Technology development and tests required to achieve greater preparedness. Still hampered by lack of re sources.

- Organizing global cooperation to support future threat response capabilities. International participation in recent conferences and workshops is an encouraging step forward.

Preparedness within the capabilities and constraints of the technology available at a given time means that efforts must be pursued continuously to define and develop preliminary mission and system design concept consistent with that state of technology. Thus, by the time a threat warning is received from the ongoing NEO search and detection activities, there would be at least a blueprint available for system development, implementation and test that could serve to accelerate the threat response as needed. At the same time detailed mission profile data, launch and arrival dates, as well as, ground support plans and schedules would have to be worked out. In this way the results of the preceding threat defense planning studies could be utilized to full advantage, updated as appropriate under the circumstances.

For an effective implementation of the intended threat response with the highest probability of success, it as imperative to launch more than one interceptor. For example, assuming a 95-percent best estimate of the success probability of the defense mission being initiated, if one interceptor is launched, then two launches would increase the combined success probability to 99.75 percent, and three launches to 99.99 percent, provided the causes of failure are unrelated, random events. Multiple launches will generally not increase the total cost by the same multiplying factor.

Conclusion

Technology requirements of missions to avert a NEO impact on Earth are dictated by the nature of the threat, i.e., object size and physical composition, orbit characteristics, arrival velocity, and the time remaining before the predicted collision. All phases of such missions place unprecedented demands on the technology to be used for their implementation, particularly the launch phase, the terminal guidance and landing phase - if planned - and the deflective impulse generation at the target, or its destruction. Robotics and automation play a key role.

The least demanding threat class may allow a defense with today's technology. Results of most of the current studies favor nuclear detonation over kinetic energy (direct impact) deflection, because it requires an up to three-orders-of-magnitude lower initial interceptor mass. On-site propulsive deflection is much less likely to be feasible with currently available propulsion technology because of the very much greater total propellant mass required, compared with the two alternative deflection modes.

For NEO defense with a short reaction time there will be practically no alternative to nuclear detonation options. However, many concerns regarding deployment risks and safeguards against misuse remain to be addressed and resolved.

System engineering methods developed for more conventional mission classes also are applicable to system selection, evaluation and implementation trades required in missions for NEO defense. Assessment of technology requirements is a principal step in this selection process, in order to eliminate impractical, potentially risky, unacceptably costly and otherwise unsuitable implementation concepts.

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